Need for Touch in Human Space Exploration: Towards the Design of a Morphing Haptic Glove – ExoSkin

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Abstract. The spacesuit, particularly the spacesuit glove, creates a barrier between astronauts and their environment. Motivated by the vision of facilitating full-body immersion for effortless space exploration, it is necessary to understand the sensory needs of astronauts during *extra-vehicular activities* (EVAs). In this paper, we present the outcomes from a two-week field study performed at the Mars Desert Research Station, a facility where crews carry out Mars-simulated missions. We used a combination of methods (a haptic logbook, technology probes, and interviews) to investigate user needs for haptic feedback in EVAs in order to inform the design of a haptic glove. Our results contradict the common belief that a haptic technology should always convey as much information as possible, but should rather offer a controllable transfer. Based on these findings, we identified two main design requirements to enhance haptic feedback through the glove: (i) transfer of the shape and pressure features of haptic information and (ii) control of the amount of haptic information. We present the implementation of these design requirements in the form of the concept and first prototype of ExoSkin. ExoSkin is a morphing haptic feedback layer that augments spacesuit gloves by controlling the transfer of haptic information from the outside world onto the astronauts' skin.

Keywords. Space; touch; haptic feedback; haptic glove; user experience; extra-vehicular activities; haptic jamming; field study; technology probes.

1 Introduction

The idea of space travel and exploring other planets in the solar system has long fascinated and inspired humans. Even before Apollo 11 landed the first humans on the Moon in 1969, researchers had already been planning and developing mission profiles to Mars [27]. NASA and ESA have both expressed plans for permanently manned lunar bases in the future [13, 15]. A base in the Moon can serve as a testbed for new technologies and the exploration of interactive techniques that enable eventual extra-terrestrial settlement and develop future space missions [28]. This ever-increasing interest in long-term missions and space settlements necessitates tackling astronauts' needs for full-body immersion and interaction with the environment.

However, the spacesuit creates an unnatural barrier resulting in the inability to feel, smell, or touch when exploring their surroundings. Since the human hand plays a major role when performing extra-vehicular activities (EVAs), the lack of haptic feedback has implications on any interaction with tools and the environment as astronauts often have to rely on visual cues. This is not always sufficient as the field of view is limited through the spacesuit and the helmet itself, which ironically makes astronauts dependent on their limited sense of touch to find objects and tools [34]. Both points suggest that astronauts cannot rely on intuitiveness when interacting with their environment, making EVAs a difficult and tedious experience. These limitations on the human senses, especially on touch, might result in a reduced ability of astronauts' to focus on their main tasks (e.g., geological sampling, scientific instrument setup and testing). With these issues in mind, technologies in human-computer interaction (HCI) should be exploited in the design context of space exploration, which will be common in the near future [18].

In this paper we focus on haptic experiences astronauts have when performing EVAs by looking at: (i) the details of the task and what they want to achieve; (ii) how they approach a task; (iii) what role their hands play in completing the task; and (iv) the types of haptic feedback that are relevant to the task. We carried out a two-week field study at the Mars Desert Research Station (MDRS), an analogue simulation environment, on a six-member crew. The MDRS reproduces an environment close to what an actual space mission is (zero gravity aside) and thus ensures a high level of ecological validity for our user study.

Over the two weeks, each crew member kept a logbook recording all their experiences whenever they performed an EVA. Inspired by work on technology probes [14], we introduced three low-level mechanical glove prototypes in the second week of the study to gain insight on the usefulness of haptic feedback in EVAs and for the completion of specific tasks assigned to the different crew members. The study concluded with an interview with each crew member capturing a more holistic understanding of the experiences from the last two weeks and highlighting the experienced difficulties and limitations when performing EVAs wearing gloves. We analysed the data and extracted individual user requirements (linked to different crew member roles or tasks), with a focus on the specific needs for haptic feedback design.

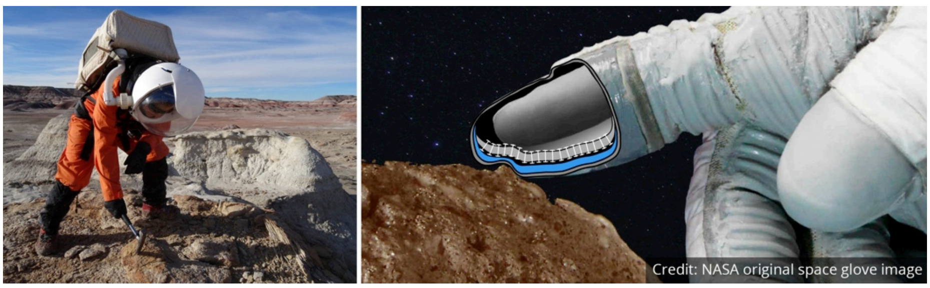

Fig. 1. ExoSkin (right) is a morphing haptic feedback layer that augments spacesuit gloves by controlling the transfer of tactile information from the outside world onto the skin. To design ExoSkin, we carried out a two-week field study at the Mars Desert Research Station (left).

Based on the findings from the field study, we identified two key design criteria of a spacesuit glove with haptic feedback: (i) transfer of the shape and pressure features of haptic information; and (ii) control of the amount of haptic information. We present the implementation of these design requirements in the form of concept and first prototype of ExoSkin (Fig. 1). ExoSkin combines both a passive mechanical and an active electrical layer in its design. The mechanical layer of the glove transfers the shape of touched objects onto the user's skin while the electrical layer controls the amount of this transfer by tuning the stiffness of the layer. This concept represents a step towards a more intuitive and natural interaction of astronauts with the environment.

Here, we not only aim to make a design contribution, but also enhance our understanding of this specific context of use, user group, and its opportunities for further experimentations in HCI and interaction design.

2 Related Work

Extra-vehicular activities (EVAs) require the astronaut to wear a spacesuit in order to perform operations away from Earth and outside spacecrafts. Due to the need to balance the protective function of a spacesuit in such harsh environments and the ergonomics of wearing one, the design of the spacesuit has gained lots of attention from space agencies, aerospace engineers, and also from HCI researchers. In this section we review previous work in two relevant areas: first, the current and future spacesuit and EVA glove designs, and second, haptic glove technology in HCI.

2.1 Spacesuit and EVA Glove Designs

Currently, spacesuits used by the United States, Russia and China are gas-filled full pressure suits. Gas-filled pressure suits have been used since the 1960s; for both lunar surface exploration and spacewalks at the International Space Station (ISS) [33]. However, there are many limitations with this type of suit such as their weight (more than 110kgs) and limited mobility and dexterity due to the need to work against the pressure of the suit [35]. The number of EVA hours for the exploration of the Moon and Mars is projected to be more than all previous decades of EVAs combined [11]. Therefore, these suits are not suitable for long hours of human planetary surface exploration where EVAs can include difficult geological traverses [35, 37].

Thus, the 'space activity suit' has been proposed as a lightweight solution that provides enhanced mobility when performing EVAs [26]. These suits are essentially skin-tight elastic bodysuits that provide mechanical counter-pressures (MCPs) to uniformly compress the skin and therefore circumvent the need for a pressure suit [35]. One of the main research efforts into realizing this type of suit is the MIT Bio-Suit system [24]. The Bio-Suit aims to allow astronauts to work, with little resistance of the spacesuits, on Mars as they would do on Earth and thus avoiding the need for task simulation or non-standard equipment [26].

Current EVA gloves are pressurized like the spacesuits, meaning the astronauts' hand will also have to work against pressure when performing a task. The effect of

EVA gloves, due to its thickness and pressure, on hand-performance such as reduced grip strength, pinch strength and tactile sensations have been documented and observed [3, 34]. However, as hand and arm fatigue has been considered the main issue, most EVA technologies focus on reducing this by implementing power-assisted exoskeletons on the gloves [7, 36]. Similar to the MCP suits, there is also research into MCP gloves. Although these gloves provide the increased dexterity needed for the hand and fingers, sensory feedback is still reduced as the thickness of the Bio-Suit is aimed at 5mm [12]. Although some studies have implemented tactile sensations for EVA gloves [1, 36], few have conducted user studies such as [1] which found that vibration feedback in the gloves to augment 'button-clicks' on a virtual keyboard increases text-entry rates and reduces errors. In this paper, we aim to investigate in detail how haptic feedback can improve the experience when performing a variety of EVA tasks drawing on haptic technologies designed and developed within HCI.

2.2 Haptic Glove Technology in HCI

Glove-based systems have been designed and developed since the 1970s to accurately track and measure hand configurations, movements and gestures [6]. These gloves, embedded with multiple sensors and trackers, have been mainly used for applications involving object selection and manipulation in virtual environments. Some of these glove-based systems also have actuators mounted to provide haptic feedback to the user's hands [5, 22, 32].

There are a variety of actuation technologies that can be used to generate haptic feedback; for example using motors, peltier elements, pin arrays and shape memory alloys [2]. Nevertheless, due to their complexity, not all technologies have been exploited in glove designs. Vibration actuators are most common as they are small and lightweight [5, 22]. The Teletact and Teletact II gloves [32] use air pressurized bladders to create force feedback in the palm. However, as far as we know, none of these glove-based systems have been applied to real-world scenarios involving the use of an actual glove with the exception of [4], which uses vibration feedback to augment obstacle distance information to firefighters.

Generally, there are three types of tactile displays [10]. The first type is pin arrays or sometimes called shape displays. These transfer vertical shape information and spatial patterns via the up-and-down movement of pins [9, 17]. Although effective at transferring most tactile information, it has been shown that lateral forces can also afford shape perception through active touch [29]. The second type uses vibration actuators and has been implemented not only in glove-based systems but many other prototype devices [2]. Although vibrations generate a 'buzzing' sensation, they can be used to produce different textures [21] and even 3D shapes [22]. The third method of producing tactile sensations is by creating lateral skin deformation using a simple comb-like system [10, 20]. This method has been shown to display Braille dots [20] and shapes and textures [19].

In this paper, we explore each of these types of tactile displays via three low-level mechanical glove prototypes, which we deployed as technology probes in the second week of our field study at MDRS.

3 Field Study

The study was conducted during a two-week field mission at the Mars Desert Research Station[1] (MDRS). The MDRS, based in the southern Utah desert, is one of several purpose-built analogue habitats that are located where environmental conditions, geological and biological features are similar to those on Mars. These habitats serve as field laboratories for researchers to run experiments that simulate the physical and psychological aspects of a Mars mission.

The MDRS is designed based on NASA's Design Reference Mission 3 and consists of a $10m^2$ two-story cylindrical habitat, a greenhouse and a small observatory. Researchers have to apply to participate and crews usually consist of six people who conduct their own independent Mars-related research. For one of the rotations, one of the authors was successfully recruited as part of a six-person crew (C6 – see Table 1). The crew was made up of four females and two males (aged between 25 and 53 years, mean 33), each with a specific role and main EVAs. C6 (author) facilitated the field study onsite and was not included in the data collection and analysis. There was a seventh person, a documentary film-maker, who was also not included in the data collection. Apart from C1 who took part two years ago, none of the other crew members had previously participated in a field rotation at the MDRS.

Table 1. Crew members' roles and main extra-vehicular activities at MDRS.

Crew members	Roles and main extra-vehicular activities
C1	*Crew commander.* Radiation dosage mitigation and radio signal measurements.
C2	*Crew medical officer.* Tele-surgery and tele-anaesthesia protocols for space.
C3	*Crew engineer.* Rover terrain testing.
C4	*Crew geochemist.* Hydrogen extraction from soil.
C5	*Crew astrobiologist.* Geological and biological sampling for extremophiles.
C6	*Crew engineer.* Exploration of haptic needs during EVAs.

During the two weeks, crew members conducted all their EVAs in analogue spacesuits, which consist of the suit, a helmet, a backpack containing the life support system (fans with portable batteries), gloves and boots (see Fig. 2). Although the setup aims to be as realistic as possible, real spacesuits cannot be provided as they are too expensive and customized for size. Thus to mimic an envisioned field mission, the analogue suits used are coveralls, the gloves used are 4 mm thick ski gloves, the boots are hiking boots and the weight combination of the helmet and backpack is around 10kg. For transport during their EVAs, crew members either walked or used all-terrain vehicles (ATVs). Each EVA generally lasts around 3 hours and an average of two EVAs are carried out every other day.

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1 http://mdrs.marssociety.org/

Fig. 2. Mars Desert Research Station in the southern Utah desert (left), and a crew member wearing the analogue spacesuit (right).

Our field study offers a high level of ecological validity, which is crucial when designing interfaces for unfamiliar environments, such as space exploration. The users are in a particular context and set of mind incorporating a plethora of factors (e.g., pressure to complete a task successfully, heavy equipment, time-delaying repercussions due to visual constraints of a spacesuit) that are very difficult to reproduce in laboratory settings. With our field study, we were able to reproduce an environment very close to what an actual space mission is (zero gravity aside), thus allowing our results to have higher external validity. Below we present the details on the conducted field study and methods used.

3.1 Study Design and Methods

The field study was divided into three parts: (i) a haptic logbook kept over two weeks, (ii) technology probes introduced in the second week, and (iii) individual interviews at the end of the two weeks. We describe each part in the following sections.

(i) Haptic Logbook: Need for Haptic Feedback in EVAs

The main aim of the logbook was to gather information on the types of EVAs that were carried out and the crew members' needs and requirements for haptic feedback when performing EVAs. Upon their return to the habitat, each crew member was asked to record and reflect about the difficulties they experienced when executing tasks during the EVA. They were also asked to describe as well as to rate their performance of the specific EVA on the day. As each crew member had their own research project and EVAs to carry out, they had their own specific tasks and equipment. A selection of these tools is shown in Fig. 3.

The logbook contained questions related to the following four aspects:

(1) the details and characteristics of the conducted EVA (short narrative on the experience and title);
(2) the context in which the EVA experience took place (presence of other crew members, physical environment, equipment used);

(3) the experienced workload during the EVA (based on the NASA TLX[2]);
(4) the relevance of haptic feedback to the specific EVA (focused on the interaction wearing the glove, desirable haptic feedback).

In the second week, the logbook was enhanced with an additional question on:

(5) how, if any, of the technology probes (described in the next section) could have assisted them in the particular EVA.

Fig. 3. Tools used by crew members during EVAs; ranging from geological hammers, spatulas, clinometer and thermometer, to pens, GPS and camera.

(ii) Technology Probes: Three Glove Prototypes

At the beginning of the second week, we introduced three glove prototypes as technology probes [14]. Technology probes is a simple and flexible approach with three interdisciplinary goals: *"the social science goal of understanding the needs and desires of users in a real-world setting, the engineering goal of field-testing the technology, and the design goal of inspiring users and researchers to think about new technologies"* [14]. This approach was particularly suitable for our field study as it enabled us to deepen our understanding of the need for haptic feedback in specific situations and for performing different tasks. The crew members were enabled to think beyond current limitations and express ideas about new solutions in the logbook and later on in the concluding interview.

For the design of the technology probes, we selected the following three types of haptic feedback mechanisms (as shown in Fig. 4):

(a) *Shape transfer mechanism (ST)*: This consisted of a rigid base holding an array of metal pins that can slide up and down. When the user makes contact with an object, the pins in contact with the object are displaced, thus transferring the shape with a resolution that depends on the density of the pins.
(b) *Vibration transfer mechanism (VT)*: This consisted of a rigid base holding an array of metal pins that has minimal horizontal and vertical movements (a few micrometres). When the user actively explores an object, the pins vibrate as a result of that action.
(c) *Lateral deformation transfer mechanism (LT)*: This consisted of a flexible silicone base onto which a matrix of comb-like plastic pins was embedded. When the user touches an object, the flexible base bends and causes the pins to move away or towards each other creating lateral stretching of the skin.

[2] NASA TLX: http://humansystems.arc.nasa.gov/groups/tlx/

Fig. 4. (Left) The three different transfer mechanisms in the technology probes integrated into individual prototype gloves; (a) shape, (b) vibration and (c) lateral deformation. (Middle) Example of the glove prototypes: vibration transfer mechanism implemented on the index and thumb. (Right) The pins of the shape transfer mechanism deforming with the contour of a ball.

We chose these three mechanisms based on typical methods of providing tactile sensations (as discussed in the *Related Work* section) and the ability to implement them without use of complicated sensors and/or actuators, so as to have no expectation of the users, environment or objects. Thus they fit the purpose of a technology probe; being simple, flexible and adaptable technologies [14].

The gloves were introduced by C6 to each crew member individually in a 15-minute session. Initial reactions were captured when the crew members were asked to use each prototype with some of the tools shown in Fig. 3. Each crew member was then asked to explore the gloves throughout the second week in relation to their EVAs and logbook entries, but not to discuss the details with the others to avoid a bias on the usefulness of three glove mechanisms. The gloves were placed on a common desk in the main habitat for the crew members to freely access whenever they wanted to.

(iii) Individual Interviews: Overall Experience
At the end of the two weeks, we conducted an interview with each crew member individually to capture their overall experiences over the two-week field mission, their EVA experiences, and their reflections on the challenges, surprises, and frustrations related to their sense of touch and the technology probes. The interviews were conducted by another researcher (co-author) on the last day at the MDRS. The interviews, which lasted about 45 minutes, took place in the greenhouse and were also based on the crew members' logbook entries (previously shared with the interviewer). All interviews were audio-video recorded for transcription and analysis purposes.

3.2 Data Analysis

The analysis process followed an open coding approach [30]. The two researchers involved in the role as crew member (C6) and interviewer conducted the first step of the qualitative coding process. To begin with, we looked at relevant themes across all collected data by carefully and repeatedly reading through the transcripts from the interviews and logbook entries. After identifying a first set of relevant themes we looked at the data from a temporal perspective in order to determine any changes of the experiences over time, especially due to the introduction of the technology probes. The outcomes from this initial coding effort was discussed with the two other co-authors and lead to further refinements of the identified themes, resulting in three main themes describing the crew members' experiences throughout EVAs. Below all three themes are described highlighting the key findings from our study.

4 Study Findings

From our analysis of the logbook and interview data, we identified three main themes that support the classification of crew members' experiences in EVAs:

(a) *Rethinking the hand/s*: Crew members became aware of the limitations and unexpected challenges of wearing both the spacesuit and gloves for EVAs, especially when performing precision work. This led crew members to re-think the 'familiar use' of their hands and focus on other and more specific parts of their hands (e.g., fingernails, palm) to complete the EVAs.

(b) *Changing practices*: The lack of haptic feedback resulted in crew members having to modify their work practices during EVAs. To complete their work, crew members exploited and enforced new strategies over time, as they could not perform tasks the same way as they would normally do with their bare hands. Specifically, they would explore new ways of using their hands (e.g., grasping with their fingertips, holding with their palm, engaging their wrist) and make use of other senses (e.g., vision) to help inform their actions.

(c) *Varying needs for touch:* Crew members have a specific understanding on how to complete their tasks; what is necessary for a successful EVA, and what they are willing to invest (e.g., taking safety and health risks into account). Despite a clear commitment to the vision of preparing humanity for life on Mars and the acceptance of challenges when wearing a spacesuit, crew members clearly expressed instances when haptic feedback was more or less desired in the interaction. When offered the three glove prototypes, crew members were able to reflect on the glove designs and their specific qualities in relation to their individual tasks and EVAs.

The first two themes represent the relevant understanding established about the specific use context, encountered limitations when wearing gloves, and crew members' experiences and exploited strategies over time. Based on this contextualisation of the design space for a haptic glove, the third and last theme represents the most relevant insights gained to inform the design process, as it narrows the interaction features down to the specific elements and needs for touch in different EVAs. Before we highlight our design solution to enhance haptic feedback, we describe three typical EVA scenarios exemplified through findings from the study and crew member quotes.

4.1 Findings exemplified through EVA Scenarios

In the following we elaborate on each of these themes through three specific scenarios representing typical EVAs from the two-week field study and crew members' feedback: (i) soil sampling for hydrogen extraction, (ii) geological sampling of rocks and soil surface and (iii) ATV terrain scouting (illustrated in Fig. 5).

Fig. 5. A few examples of EVAs performed during the field study: (a) soil sampling for hydrogen extraction; (b) examining rocks during geological sampling and (c) ATV terrain scouting.

Soil Sampling for Hydrogen Extraction

In this EVA, the crew member had to extract soil samples between 5cm and 10cm below the surface. The samples will later be brought back to the habitat for water content analysis. The tools used were a hammer to loosen up the soil, a spade to collect it, a bag to contain the soil and an infrared thermometer to measure the temperature of it. The crew member had to kneel down to perform the tasks.

As the whole crew, apart from C1, were wearing an analogue spacesuit for the first time, their excitement was coupled with the realisation of how the spacesuit impacts on their tasks within the EVA. The feeling of enjoying the challenge but also acknowledging its difficulty was captured by C4 as follows: *"I was like, 'Wow, I'm going to be like an astronaut!' But, after wearing it [spacesuit], it was really a heavy task…The first time was kind of exciting, but slowly, as I started walking and when I had to sit and dig it was very difficult for me to keep my legs in the right position"*.

On establishing a new understanding of the hands, C4 comments in the interview: *"So, you will work according to that [limitations]. It's just that for 27 years, I am working with these fingers, I'm comfortable with that. It's like that. So, I just took some time in the beginning. It was difficult to understand how my hands are behaving with those gloves"*.

C4 expressed frustration on the difficulty of moving with the heavy spacesuit: *"Wearing the backpack and the helmet, it was very uncomfortable, very uncomfortable… your backpack is heavy and you have to walk with it"* and the tools slipping out of the hand when digging for soil due to incorrect grip and not being able to feel the buttons on the thermometer; *"Oh my God, I never thought it would be so difficult"* but at the same time states that "*I was trying to cope with it, because I knew that it was a challenging task. I can't expect that things are going to be rosy*".

In the logbook, C4 mentions that although the task with the gloves became easier after the first EVA, grasping of tools was still difficult. C4 states; *"It was quite difficult to grasp the tools like the spade and the hammer for digging. With one hand, I felt as if I was not able to apply the right pressure to the tools [for] hitting or digging the soil. I could apply the right pressure to the radio button and it was much easier. It was so probably because of my understanding of the gloves from the first EVA"*.

In the logbook, C4 also comments that haptic feedback would be helpful to "*…which can make easy to sense where the fingers not just the palm [are on the tool] as fingers help hold the tool and have the right grip on it"*. When presented with the technology probes, C4 preferred a combination of the shape transfer (ST) and the lateral deformation transfer (LT) mechanism. In the interview, C4 states that *"This one [ST] I felt was very good for such devices … If you have this one button to press, this would also work, because this is quite hard as a surface and you know what you're hitting. You know the difference of the protrusion of the button and the flatness of the other part… they are better for this precision type of work"*.

Overall, this example on soil sampling highlights the initial reactions of crew members on the new situation and the realisation of the limitations of their hands in use. While the statements exemplify that the difficulties of wearing gloves were expected, it still took them time to realise and adjust to the unfamiliar behaviour of their hands and the lack of sensations and accuracy when performing simple tasks.

Geological Sampling of Rocks and Soil Surface

In this EVA, the crew members had to collect geological samples from various locations. This EVA involved examining the outcrop and its density (whether hard and solid or soft and easy to break up), look at patterns in the rock (e.g., layer or signs of deformation) and inspect its grain size. The tools used were a geological hammer to break the rocks, a shovel for digging the soil, a camera to take photos of the samples, bags to contain the samples, a compass-clinometer to perform some measurements and a pen and notebook to record observations. If a sample is small, a spatula is used.

C5 recalled some thoughts before going on the first EVA: *"Oh, no, doing biological sampling and writing, how am I going to do it? But I find that when you have to, you have to. You find a way to do things"*.

Upon realising the limitations on the EVA tasks, C5 noted in the logbook: *"My main problem was the decreased agility caused by the gloves. It made all the tasks much more difficult, time consuming and messy. It was trickier because I couldn't feel the edges of the aluminium foil around the spatula and cannot apply pressure to properly peel it off. However, writing with the gloves was a challenge and the writing in my notebook is very messy as the glove was thick and I could not hold the pen properly. For geological samples it would be good to touch the samples and feel the grain size (whether it's gritty or not). This is currently inhibited by the gloves."*

As in the previous scenario, the hands were sometimes not used in the normal way. C1 describes employing different methods for writing; *"I'd have to grip it as tight as I could, just to make sure the pen was secure, even though I couldn't quite tell where my fingers were in contact with the pen, just such that there was a solid surface"*.

C1 also pointed out that haptic feedback was not always necessary for all tasks: *"For this EVA in particular, such sensation would have made writing easier, brushing items clean easier, peeling tinfoil off wrapping, open/closing the briefcase, and opening/closing zip-lock bags. Due to the loads required, I think very little would have been gained when using the digging shovel. In fact, less sensation helped in terms of mitigating against fatigue"*.

C5 reflected on a combination of the ST and LT technology probes in relation to the task: *"Well, because [ST] takes the shape of what you're trying to press and* *touch. I think I found it easier to identify the buttons and things. But then, on the other hand, this glove [LT], the advantage was that because this is flexible, unlike [ST] It's thinner, I felt like I had, I guess, a bit more control of what I'm touching, I was able to feel the size of the button, not just the button coming at me."*

Overall, this example on geological sampling advances on the observations from soil sampling by giving more insights into the need for more fine-granular haptic feedback when touching a rock or handling small tools. However, at the same time, it brings to the fore the desire for an adaptable glove; so that it allows for less haptic feedback when digging on hard surfaces to avoid hand fatigue. It demonstrates the importance of finding a balance between increased haptic sensations for one task versus limiting the transfer of haptic sensations onto the human hand in another task, when performing the same type of EVA.

ATV Terrain Scouting

In this EVA, the crew members used the ATV to scout terrain for either rover testing or collecting geological samples. The other tool mainly used here was a walkie-talkie for communications between crew members and with the habitat.

From the logbook, C1 mentions safety implications of the lack of haptic feedback when driving the ATVs as it was difficult to feel the controls of buttons and throttle properly. C1 also mentions that he would make mistakes when carrying out certain tasks especially when using the walkie-talkie. C1 comments: *"I sometimes did not make the correct contact with the walkie-talkie communication button and would accidently release it half-way through a 10-count."*

From the logbook, C1 states; *"The gloves impeded my ability somewhat regarding the controls of the ATV, the buttons and the throttle - a necessary evil as without them, my fingers would have gotten very cold very quickly and my senses would have been in a far worse state…Where my thumb was, exactly in relation to the throttle level, was sometimes difficult to tell if I didn't look down. This could be considered dangerous when moving. My thumb could be half a centimetre below or above the throttle making the force I needed to input for a given amount of throttle variable. With the vibrations through the ATV (engine and interaction with trail surface) coupled to this lack of sensation, could lead to accidents."*

The glove, in most of the cases, does not allow enough haptic feedback, and thus limits one's ability to feel or receive any confirmation on an action. Most of the crew members start employing other senses, especially vision, to get their work done. C1 summarises as follows: *"The gloves are like oven mittens; you can't quite… It's like you've lost your senses in your hands. More than feel, you're using your eyes to see exactly what your hands are doing"*.

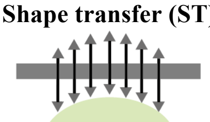
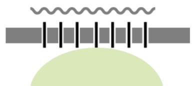
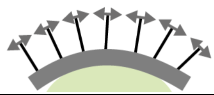
In terms of haptic feedback based on the technology probes, C1 refers to the combination of ST and LT mechanisms as ideal as it will allow for more tactility and also increases precision when performing a task through ensuring grip on a tool (so that there is no need to exaggerate the pressure too much).

Overall, this example on terrain scouting further highlights that the need for more tactile sensations varies throughout an EVA (pressing buttons versus ensuring grip when steering the ATV). Moreover it also clearly points to the cross-sensory compensation for the lack of haptic information (i.e., through visual cues).

4.2 Crew Preferences based on the Technology Probes

Overall, all crew members preferred the ST glove because it projects the shape, curvature and texture onto the hand which is useful for interacting with tools and objects. Three crew members (C1, C4 and C5) however saw this glove ideally combined with the LT glove, because its flexibility allows it to amplify pressure feedback. The VT glove was not preferred by anyone specifically because of the drawbacks of limited flexibility and shape and pressure feedback.

Table 2. Summary of crew experiences of glove design based on logbook and interview

Shape transfer (ST) 	**Vibration transfer (VT)** 	**Lateral transfer (LT)** 
The pins conform to the object's shape allowing one to be precise when pressing different buttons or when feeling and holding tools. This provides a high shape resolution allowing easy identification of general shapes and subtle differences in objects.	Different textures can be felt, but it is difficult to feel edges, sharpness or curvatures of objects.	Some shapes and textures can be felt, but edges of objects are not so clear. Compared to ST, this has a poorer shape resolution. However, it can transmit pressure sensations when pressing buttons or gripping tools.

4.3 Summary and Implications for the Glove Design

Overall, crew members felt that the spacesuit and gloves created an additional burden to their work and made it more stressful and frustrating, especially considering the limited time they can spend on each EVA. Haptic feedback would have easily allowed them to perform some of their tasks more efficiently. More importantly, in terms of designing for haptic feedback, we found that there is not only a need for touch, but a need for varied levels of touch in different scenarios.

Based on the field study, which provided us with a clear understanding of the environment astronauts are operating and the limitations they face during EVAs, we started a design process that took not only the findings from the technology probes (the initial prototypes) into account but in particular the lessons from the varied needs of haptic feedback in the diverse sets of tasks and EVAs carried out by the crew.

In the following section, we present our conceptual and prototypical design of ExoSkin, which is based on two main design requirements:

(1) *Transfer of the shape and pressure features of haptic information*: The glove needs to be designed in a way that haptic information is transferred from the outside world onto the hand supporting differences in the shape contours (e.g., edges, curves, surface irregularities) to help astronauts easily identify objects. Pressure information is also important to enable astronauts to better judge the amount of pressure and grip to apply onto objects or tools.

(2) *Control of the amount of haptic information:* The variety of EVA tasks needs to be considered in the glove design such that it can equally support more sensations when needed for fine motor skills involved in geological sampling and less haptic feedback when driving an ATV through an uneven terrain.

5 EXOSKIN

In this section, we propose the concept of ExoSkin; a spacesuit haptic feedback layer that is able to selectively transmit haptic information from outside of the suit to the inside, i.e. onto the human skin. Based on the two main design criteria summarised in the previous section, we implemented ExoSkin in two layers: first, a passive mechanically actuated layer consisting of free-moving pins on a flexible material; and second, an active electrically-controlled jamming layer for programmable stiffness (Fig. 6).

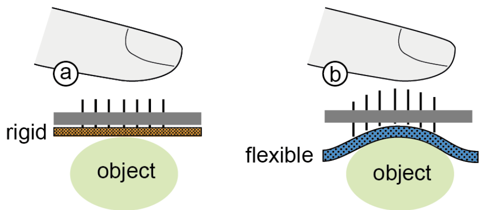


Fig. 6. ExoSkin layers. (a) When the jamming layer is rigid, haptic feedback is minimally transferred; and (b) when the jamming layer is flexible, the amount of haptic feedback that is transferred depends on the amount of air in the jamming layer.

5.1 Implementation

In the field study, we found that the shape transfer mechanism to be the preferred method for haptic feedback. We also found that a combination of the shape and lateral deformation transfer mechanisms was preferred by a few of the crew members. With both these points in mind, instead of implementing the shape transfer mechanism on a rigid base, we now implement it on a flexible silicon layer. A similar device [16] has shown that a pin array on a flexible base can even increase the sensitivity to surface asperities as it produces both normal and tangential forces to the skin.

As we observed for some tasks, the crew members did not want the gloves to transfer all of the haptic feedback. Thus, we added a second layer that is able to control the amount of haptic information that is being transferred. Although this layer can be implemented with actuated pins, we decided to create this second layer of ExoSkin using the principles of jamming due to its advantages as described below.

Jamming interfaces have been used to create a variety of objects and layers with electronically programmable stiffness [8, 25]. [25] demonstrated that thin layers of jamming can be used to create a shoe with different stiffness distributed all across its frame. Thus, the shoe can be configured for different scenarios such as walking, hiking or running. We draw inspiration from this and apply it to ExoSkin.

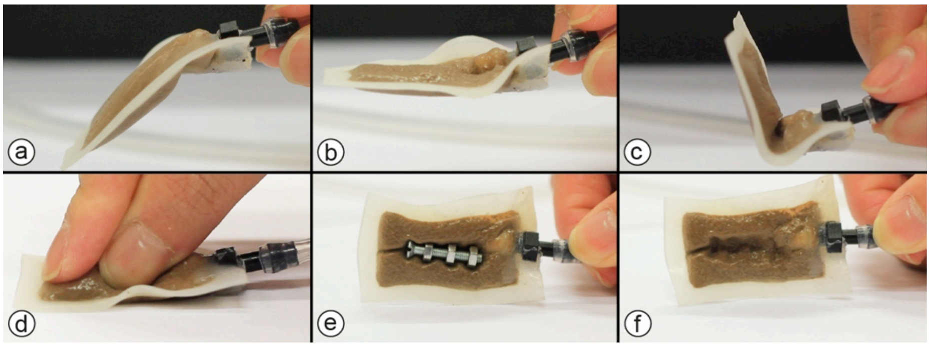


Fig. 7. Jamming layer implementation. (a) Layer is flexible; (b) it is rigid when air is removed; (c) a rigid layer can take shape; (d) when holding onto objects; (e) the layer can maintain grip on them and (f) it can hold the shape of the objects.

From initial prototyping tests, we found that jamming has the following advantages. Firstly, it allows us to control the rigidity of the layer in a continuous way, thus we can control the amount of haptic information that gets transferred. Secondly, due to its ability to deform and maintain rigidity, we are also able to use it for take shape and also grip objects (Fig. 7). The jamming layer can potentially act as an exoskeleton by retaining its shape when it is stiff. This is useful, especially for astronauts, as it can also be exploited as an exoskeleton for holding onto objects or surfaces. If the jamming layer was implemented in the whole hand, the glove can stiffen up and maintain form around tools thus avoiding occurrences of losing grip on tools.

We implemented ExoSkin in the form of fingertips of a glove as shown in Fig. 8. The ExoSkin prototype consists of two layers as described below:

(1) *Mechanical layer for haptic transfer:* This consists of a flexible layer made from 4mm polyester fabric embedded with a matrix of free-moving plastic pins. This corresponds to implementing a combination of the shape and lateral deformation transfer mechanism (as used in the field study).

(2) *Electronic layer for haptic control:* This consists of a bladder made of silicone containing coffee grains. This bladder has a snake-like pattern in order for the coffee grains to remain homogenously distributed. Due to the gravity, having a bladder without any patterns or chambers would cause the grains to collect on the sides depending on the orientation of the glove. Each bladder is then connected to a peristaltic pump that controls the amount of air in the bladder and thus its flexibility.

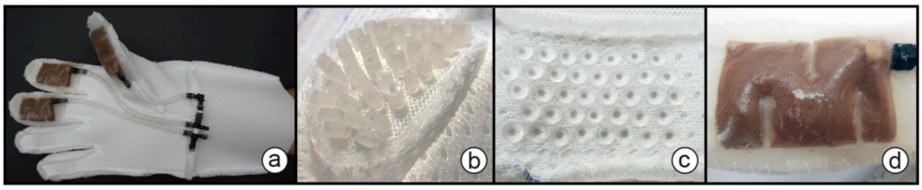


Fig. 8. First prototype of ExoSkin. (a) Glove prototype; (b) pin array on the inside which contacts the skin; (c) pin array on the outside and (d) jamming layer with chambers to ensure the grains stay homogeneously distributed.

The design of ExoSkin offers three advantages: (a) transfer of shapes and pressure information; (b) continuous control of this transfer and (c) the ability to maintain grip on objects. Although implemented at the fingertips at the moment, ExoSkin can be extended to the whole hand and even to other parts of the body (e.g. arms or feet).

6 Conclusion and Future Work

Our research focused on the need for haptic feedback during extra-vehicular activities. The combination of the field study at the Mars Desert Research Station and the use of initial ExoSkin prototypes as technology probes within the study initiated a promising design process towards a morphing haptic feedback glove.

We have identified that not only is there a need to enhance haptic feedback when wearing gloves, there is also a need to reduce haptic feedback for certain tasks to improve an EVA experience. Moreover, depending on a crew member's role and task, more specialised glove design need to be considered. Apart from the three scenarios discussed in this paper, other crew member roles need to be taken into account. For example, a crew scientist could require sterile gloves and a crew medic could require intelligent gloves for capturing biometrics from a patient. These specialised EVA scenarios open up future design directions for HCI and haptic technology.

Further investigations are needed to create higher-fidelity prototypes and evaluate their usefulness for specific tasks. Although we can build on previous works on perception studies of pin arrays [e.g. 23, 31], future studies will also need to investigate perception thresholds with varying stiffness and thickness of the jamming layer.

Moreover, in order to achieve a functional device, we believe our work can be supported with new technologies from areas such as material engineering. Active materials, such as shape memory polymers, and textile architectures, which these materials are built into, are already being investigated to create morphing structures that can actively compress to provide the pressures needed for the Bio-Suit system [12]. For the jamming layers, [25] demonstrated that thin layers can be weaved together to form different structures. Instead of having pins embedded through a fabric, 3D textile technologies drawn upon to create pin-like structures, so that the mechanical layer does not have holes. Although we implemented ExoSkin using a pin array combined with a jamming layer, many other technologies could be used (e.g., pin array combined with ferrofluid or just an array of actuated pins). ExoSkin could be applied in other work environments, which involve both the need to wear gloves and precision work. For example, tactile sensation is highly important for extreme work conditions like firefighting where there is impaired vision due to smoke and low light levels [4].

In conclusion, the insights gained from our field study did not only inform and steer the design of a new haptic glove, but also enabled us to establish a richer understanding of a use and interaction context – human space exploration – not yet mainstream within HCI and interaction design research. This is only the first of many studies to come considering the global ambition to prepare humanity for life on Mars.

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References

1. Adams, R.J. et al. Glove-Enabled Computer Operations (GECO): Design and Testing of an EVA Glove Adapted for Human-Computer Interface. In: 42nd AIAA ICES, 1-23 (2013)
2. Benali-Khoudja, M., Hafez, M., Alexandre, J.M. and Kheddar, A. Tactile Interfaces: a State-of-the-art Survey. In: 35th Int. Symp. on Robotics, 721-726 (2004)
3. Bishu, R.R., and Klute, G. The Effects of Extra Vehicular Activity (EVA) Gloves on Human Performance. Int. J. Industrial Ergonomics, 16(3), 165-174 (1995)
4. Carton, A. and Dunne, L.E. Tactile Distance Feedback for Firefighters: Design and Preliminary Evaluation of a Sensory Augmentation Glove. In: 4th Aug. Human, 58-64 (2013)
5. CyberTouch. *http://www.cyberglovesystems.com/*
6. Dipietro, L., Sabatini, A.M. and Dario, P. A Survey of Glove-Based Systems and Their Applications. IEEE Trans. Syst. Man. Cybern. C App. Rev., *38*(4), 461-482 (2008)
7. Favetto, A., Chen, F.C., Ambrosio, E.P., Manfredi, D. and Calafiore, G.C. Towards a Hand Exoskeleton for a Smart EVA Glove. In: IEEE ROBIO*,* 1293-1298 (2010)
8. Follmer, S., Leithinger, D., Olwal, A., Cheng, N. and Ishii, H. Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices. In: 25th UIST, 519-528 (2010)
9. Garcia-Hernandez, N., Tsagarakis, N. G., and Caldwell, D. G. Feeling Through Tactile Displays: A Study on the Effect of the Array Density and Size on the Discrimination of Tactile Patterns. IEEE Trans. On Haptics, 4(2), 100-110 (2011)
10. Hayward, V. and Cruz-Hernandez, M. Tactile Display Device using Distributed Lateral Skin Stretch. In: Haptics Symposium (HAPTICS), 69, 2 (2000)
11. Hoffman, S.J. Advanced EVA Capabilities: A Study for NASA's Revolutionary Aerospace Systems Concept Programs. *NASA/TP—2004–212068* (2004).
12. Holschuh, B., Obropta, E., Buechley, L., and Newman, D. Materials and Textile Architecture Analyses for Mechanical Counter-Pressure Space Suits using Active Materials. In: AIAA SPACE Conf. and Expo (2012)
13. Hovland, S. ESA Human Lunar Architecture Activities. In: Inter. Lunar Conf. (2005)
14. Hutchinson, H. et al. Technology Probes: Inspiring Design For and With Families. In: CHI, 17-24 (2003)

15. Kennedy, K.J., Toups, L.D. and Rudisill, M. Constellation Architecture Team–Lunar Scenario 12.0 Habitation Overview. In: Earth and Space, 989-1011 (2010)
16. Kikuuwe, R., Sano, A., Mochiyama, H., Takesue, N., and Fujimoto, H. Enhancing Haptic Detection of Surface Undulation. ACM Trans. on Applied Perception, 2(1), 46-67 (2005)
17. Killebrew, J.H., Bensmaia, S.J., Dammann, J.F., Denchev, P., Hsiao, S.S., Craig, J.C., and Johnson, K.O. A Dense Array Stimulator to Generate Arbitrary Spatio-Temporal Tactile Stimuli. Journal of Neuroscience Methods, *161*(1), 62-74 (2007)
18. Kostakos, V. The Challenges and Opportunities of Designing Pervasive Systems for Deep-Space Colonies. Personal and Ubiquitous Computing, *15*(5), 479-486 (2011)
19. Lévesque, V., and Hayward, V. Tactile Graphics Rendering using Three Laterotactile Drawing Primitives. In: Haptics Symposium (HAPTICS), 429-436 (2008)
20. Lévesque, V., Pasquero, J., Hayward, V., and Legault, M. Display of Virtual Braille Dots by Lateral Skin Deformation: Feasibility Study. ACM Trans. Applied Perc. 2(2), 132-149 (2005)
21. Martínez, J., García, A. S., Martínez, D., Molina, J. P., and González, P. Texture Recognition: Evaluating Force, Vibrotactile and Real Feedback. In: INTERACT, 612-615 (2011)
22. Martínez, J., García, A., Oliver, M., Molina Masso, J. and González, P. Identifying 3D Geometric Shapes with a Vibrotactile Glove. In: *IEEE CGA*, 99 (2014)
23. Nakatani, M., Kawakami, N., and Tachi, S. How Human Can Discriminate Between Convex and Concave Shape from the Tactile Stimulus. In: Ann. Conf. Cog. Science (2007)
24. Newman, D.J., Canina, M. and Trotti, G.L. Revolutionary Design for Astronaut Exploration - Beyond the Bio-Suit System. In: *Proc. STAIF,* 880(1)*,* 975-986 (2007)
25. Ou, J., Yao, L., Tauber, D., Steimle, J., Niiyama, R. and Ishii, H. jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming. In *Proc. TEI*, 65-72 (2014)
26. Pitts, B., Brensinger, C., Saleh, J., Carr, C., Schmidt, P. and Newman, D. Astronaut Bio-Suit for Exploration Class Missions. *NIAC Phase I Final Report, Cambridge, MIT* (2001).
27. Portree, D.S. Humans to Mars: Fifty Years of Mission Planning, 1950-2000. *NASA/SP-2001-4521* (2001).
28. Purves, L.R. Use of a Lunar Outpost for Developing Space Settlement Technologies. In: *Proc. AIAA Space* (2008)
29. Robles-De-La-Torre, G., and Hayward, V. Force Can Overcome Object Geometry in the Perception of Shape through Active Touch. Nature, 412(6845), 445-448 (2001)
30. Saldana, J. The Coding Manual for Qualitative Researchers. SAGE Publications (2012).
31. Shimojo, M., Shinohara, M., and Fukui, Y. Human Shape Recognition Performance for 3D Tactile Display. Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, 29(6), 637-644 (1999)
32. Stone, R.J. Haptic feedback: A Brief History from Telepresence to Virtual Teality. In: *Haptic Human-Computer Interaction*, Springer Berlin, 1-16 (2001)
33. Thomas, K.S. and McMann, H.J. *US Spacesuits*. Springer (2011).
34. Thompson, S., Mesloh, M., England, S., Benson, E. and Rajulu, S. The Effects of Extravehicular Activity (EVA) Glove Pressure on Tactility. In: *Proc. Human Factors and Ergonomics Society,* 55(1), 1385-1388 (2001)
35. Webb, P., Cole, C. and Hargens, A. The Elastic Space Suit: Its Time Has Come. In: *Proc. ICES* (2011)
36. Yamada, Y. et al. Proposal of a SkilMate Hand and its Component Technologies for Extravehicular Activity Gloves. In: *Advanced Robotics*, *18*(3), 269-284 (2004)
37. Young, D. and Newman, D. Augmenting Exploration: Aerospace, Earth and Self. In: *Wearable Monitoring Systems*, Springer US, 221-249 (2011)